AD-A278 988

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE March 22, 1994

3. REPORT TYPE AND DATES COVERED Final Technical Report; 11/1/90-10/31/92

4. TITLE AND SUBTITLE
Unsteady Structure of Leading-Edge Vortices on a Delta Wing

5. FUNDING NUMBERS
AFOSR-91-0005
2307/A3

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8. PERFORMING ORGANIZATION REPORT NUMBER
AEOSR-TR- 94 0269

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research
110 Duncan Avenue, Suite B115
Bolling Air Force Base, D. C. 20332-0001

NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFOSR-91-0005

11. SUPPLEMENTARY NOTES

DTIC ELECTE MAY 06 1994 S G D

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

94-13594

13. ABSTRACT (Maximum 200 words)

The overall objective of this research program was to characterize the unsteady flow structure on wings having swept edges. Wings were subjected to global control, involving motion of the entire wing, and local control, involving perturbations at specified locations on the surface of the wing. New types of experimental facilities and image acquisition and processing techniques have allowed determination of the instantaneous vorticity distributions and streamline patterns of the flow. The occurrence of vortex breakdown and stall and their phase shifts relative to the wing motion and to control at the leading-edges have been interpreted in terms of new flow mechanisms.

94 5 05 078

Codes	
Dist	Avail and/or Special
A-1	

14. SUBJECT TERMS
Delta Wings, Vortex Breakdown, Laser Diagnostics

15. NUMBER OF PAGES 7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 1

Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. Z39-18

AEOSR-TR- 94 0269

FINAL TECHNICAL REPORT FOR AFOSR GRANT
UNSTEADY STRUCTURE OF LEADING-EDGE VORTICES ON A DELTA WING

P.I. Name: Rockwell, Donald O.
Institution: Lehigh University
Contract/Grant Number: AFOSR-91-0055
Effective Dates: November 1, 1990 to October 31, 1993

1. OVERVIEW OF OBJECTIVES

The overall goal of this research program is to characterize the unsteady flow structure on wings having swept edges. Emphasis is on three parallel endeavors: (i) development of new experimental facilities and approaches; (ii) advancement of new types of image acquisition and image processing techniques that allow quantitative assessment of the instantaneous, unsteady flow structure; and (iii) determination of the detailed flow structure and loading on generic types of wings. These wings are subjected to global control, involving motion of the entire wing, or local control, involving perturbations at specified locations on the surface of the wing.

Development of new types of experimental facilities and instrumentation strives to simultaneously apply local control, characterize the instantaneous, quantitative flow structure and eventually determine the unsteady loading on the wing. To this end, efforts have been on implementing integrated systems of controlling the wing, illuminating the flow with scanning lasers and acquiring instantaneous images using advanced PIV techniques.

Development of new types of quantitative visualization techniques focuses on advanced types of high-image-density particle image velocimetry (PIV) and novel image processing approaches that allow determination of the flow topology which, in turn, dictates the loading of the wing.

Pursuit of new classes of instantaneous flow structure involves determining possible phase shifts between the instantaneous location of vortex breakdown and the position of the wing and identification of corresponding flow mechanisms that provide the potential for control at high angle-of-attack.

2. SUMMARY OF RESEARCH ADVANCES

During this program, substantial advances have been made in our understanding of the inherent flow structure on delta wings and its control using global and local techniques. These advances are described in detail in the publications listed in Section 3. Brief summaries of these advances are given in the following.

2.1. *Response of vortex breakdown on a delta wing following a transient maneuver.* The unsteady relaxation process of vortex breakdown was examined by acquiring successive, instantaneous images of the azimuthal vorticity through the centerplane of the vortex immediately following a pitch-up maneuver. These results show, for the first time, the criteria for vortex breakdown in terms of the azimuthal vorticity contours and selected streamline patterns. Moreover, the increase in scale of the turbulent vortical structures in the breakdown region with increasing chordwise distance along the wing is in accord with spectra of surface pressure measurements; this observation has important implications for buffeting phenomena.

2.2 *Vortex breakdown mechanisms for transient maneuvers to very high angle-of-attack.* Following a pitch-up maneuver to very high angle-of-attack, the instantaneous structure of the leading-edge vortex undergoes drastic alterations. It involves a very rapid penetration of concentrated vorticity into the upstream, interior region of the leading-edge vortex. The abrupt occurrence of this process marks a large change in propagation speed of the vortex breakdown along the wing. By designing control techniques to enhance or retard this penetration process, it should be possible to alter the lift and moment during rapid maneuvers.

2.3 *Stall manipulation on delta wings at high angle-of-attack via leading-edge perturbation.* Existence of a fully-stalled condition at high angle-of-attack is associated with a substantial loss of controllability and lift. By subjecting a delta wing to pitching oscillations at a relatively high dimensionless frequency, it is possible to generate pronounced concentrations of vorticity that are associated with well-formed leading-edge vortices over a portion of the oscillation cycle. This structure of the leading-edge vortex can be highly repeatable from cycle to cycle or repeatable every second cycle, corresponding to a subharmonic mode. This response of the leading-edge vortices has important implications for application of local control involving leading-edge flaps or unsteady blowing from a slit.

2.4 *Manipulation of vortex breakdown and stall by blowing/suction at the leading-edge of a delta wing.* The time-averaged response of vortex breakdown and stall on a delta wing to steady and unsteady blowing/suction along the leading-edge of the wing has been examined. Alternate blowing and suction, involving no net mass addition to the flow, is shown to be very effective in retarding the onset of breakdown and stall. These phenomena are characterized in terms of sectional streamlines and vorticity contours, which show the distortion and location of the leading-edge vortex as a function of time.

2.5 *Vortex breakdown on a stationary delta wing.* Although the location of breakdown on a stationary wing is typically viewed to be a steady phenomenon, experimental observations indicate that substantial streamwise fluctuation of the breakdown position can occur. Examination of this unsteady meandering of the breakdown has focused on characterization of the primary mode of vortex breakdown, i.e., spiral versus bubble, while monitoring the streamwise excursions of the instantaneous breakdown position. Approximately one hundred instantaneous realizations of the flow structure have been obtained. Extensive data analysis is still underway, in order to provide insight into the mechanisms that drive the self-excited, streamwise fluctuations of the breakdown process.

2.6 *Development of new experimental approaches.* Major initiatives have centered on quantitative characterization of the unsteady flow structure, which, in turn, dictates the unsteady loading. In general, these efforts have involved the development of new approaches to image acquisition and image processing.

(i) *Laser scanning and image shifting techniques.* Development of scanning techniques involving oscillating and rotating mirrors, first developed by the author's group and further refined during the past year, have been linked to image shifting techniques in order to allow characterization of the instantaneous velocity and vorticity fields of complex, separated flows occurring on delta wings. Implementation of this system has provided the first characterization of the instantaneous structure of the vortex breakdown process of leading-edge vortices.

(ii) *Processing of high-image-density PIV images.* Efforts have focused in implementation of a state-of-the-art high resolution image scanning system, which represents particle images in digital form and, in turn, allows rapid, digital manipulation of the particle image field to generate a velocity field. In doing so, new types of Fourier transform and correlation techniques have been developed. Various peak fitting approaches have been evaluated in order to optimize the accuracy of the velocity field. Moreover, development of new types of vorticity correlation functions, applicable to an entire image of the flow provide insight well beyond that attainable with classical point measurement approaches.

(iii) *Development of PIV cinematography system.* The evolution in time of patterns of vortex breakdown and stall is of major interest. Substantial effort has been dedicated to implementation of a custom-designed cinema camera, which allow the first cinematographic characterization of these types of flow patterns. In essence, each frame of a long spool (35 mm) film corresponds to a PIV image, allowing pseudo-real-time construction of the flow, as well as innovative types of correlations between successive images.

3. PUBLICATIONS

A number of publications are currently in preparation. In the following, only those that are either in press or have appeared will be listed.

3.1 *Publications in Reviewed Journals*

"Flow Structure on a Stalled Delta Wing Subjected to Small-Amplitude Pitching Oscillations", submitted to *AIAA Journal* (with K. Cipolla).

"Three-Dimensional Flow Structure on Delta Wings at High Angle-of-Attack: Experimental Concepts and Issues", submitted to *AIAA Journal.* (Also AIAA Paper No. 93-0550.)

"Transient Structure of Vortex Breakdown on a Delta Wing at High Angle-of-Attack", *AIAA Journal* (in press) (with J.-C. Lin).

"Cinematographic System for High-Image-Density Particle Image Velocimetry", *Experiments in Fluids* (in press) (with J.-C. Lin).

"Interaction of a Streamwise Vortex with a Thin Plate: A Source of Turbulent Buffeting", *AIAA Journal* (in press) (with A. Mayori).

"Laser-Scanning Particle Image Velocimetry Applied to a Delta Wing in Transient Maneuver", *Experiments in Fluids*, Vol. 15, No. 3, pp. 159-167, 1993 (with C. Magness and O. Robinson).

"Construction of Three-Dimensional Images of Flow Structure Via Particle Tracking Techniques", *Experiments in Fluids*, Vol. 14, pp. 257-270, 1993 (with O. Robinson).

"Instantaneous Topology of the Unsteady Leading-Edge Vortex at High Angle of Attack", *AIAA Journal*, Vol. 31, No. 8, pp. 1384-1391, 1993 (with C. Magness and O Robinson).

"Control of Vortices on a Delta Wing by Leading-Edge Injection", *AIAA Journal*, Vol. 32, No. 7, 1993 (with W. Gu and O. Robinson).

"High-Image-Density Particle Image Velocimetry Using laser Scanning Techniques", *Experiments in Fluids*, Vol. 14, pp. 181-192, 1993 (with C. Magness, J. Towfighi, O. Akin and T. Corcoran).

"Instantaneous Structure of Vortex Breakdown on a Delta Wing via Particle Image Velocimetry", *AIAA Journal*, Vol. 31, No. 6, pp. 1160-1162, 1993 (with J. Towfighi).

"Unsteady Crossflow on a Delta Wing Using Particle Image Velocimetry", *AIAA Journal of Aircraft*, Vol. 29, No. 4, pp. 707-709,1992 (with C. Magness and O. Robinson).

"Effect of Concentration of Vortices on Streakline Patterns", *Experiments in Fluids*, Vol. 10, pp. 294-296, 1991 (with I. Gursul).

3.2 *Books or Book Chapters Published*

Naudascher, Eduard and Rockwell, Donald O. An Engineering Guide to Flow-Induced Vibrations, Balkema press, Rotterdam (in press). This book provides an overview of the wide variety of mechanisms associated with flow-induced vibration and noise generation.

4. GRADUATE STUDENTS

Magness, Charles	Mechanical Engineering	Ph.D.	1991	US
Cipolla, Kimberly	Mechanical Engineering	M.S.	1992	US
Cipolla, Kimberly	Mechanical Engineering	Ph.D.	1995 (expected)	US
Mayori, Alejandro	Mechanical Engineering	M.S.	1993	Non-US
Towfighi, Joseph	Mechanical Engineering	M.S.	1993	US
Vorobieff, Peter	Mechanical Engineering	Ph.D.	1996 (expected)	Non-US

5. POST-DOCTORATES/RESEARCH ASSOCIATES

Gu, Weikai	Mechanical Engineering	Non-US
Lin, Jung-Chang	Mechanical Engineering	Non-US
Robinson, Olivier	Mechanical Engineering	Non-US

6. AWARDS

Cipolla, Kimberly, M., Amelia Earhart Fellowship, Zonta Foundation, 1992
Mayori, Alejandro, LASPAU Fellowship, Fulbright Commission, 1992
Rockwell, Donald O., Paul B. Reinhold Professorship, Lehigh University
Rockwell, Donald O., Elected Fellow of American Physical Society (for fundamental contributions to our understanding of vortices and their interaction with structures), 1993
Rockwell, Donald O., Nominated (by a national committee) for candidacy for Vice-Chair (eventually Chair) of American Physical Society, Fluid Dynamics Division, 1993

7. INTERACTIONS (COUPLING ACTIVITIES)

(i) Workshops

The principal investigator, jointly (with Major Daniel Fant of AFOSR) organized the *Workshop on Supermaneuverability: Physics of Unsteady Separated Flows at High Angle-of-Attack* held at Lehigh University, April 9 and 10, 1992. This major effort brought together international authorities on high angle-of-attack aerodynamics, and resulted in a white paper defining the most critical, unresolved issues. At a subsequent workshop, entitled *AFOSR/Wright Laboratories/FJSRL High Lift Concepts Workshop*, held at the U. S. Air Force Academy on October 13-14, 1993, the PI presented a state-of-the-art assessment "Three-Dimensional Flow Past Lifting Surfaces: Physics and Flow Control Concepts", which defined key research issues.

(ii) Collaboration/Communication with Parallel Research and Development Groups

A number of ongoing interactions have been established with researchers at Wright Patterson Air Force Base (WPAFB) and NASA facilities, as well as other universities:

- *Miguel Visbal and Ray Gordnier (WPAFB).* DNS of flow past stationary pitching and rolling delta wings to complement PIV investigations at Lehigh.

- *Jerry Jenkins (WPAFB).* Experimental studies of flow past pitching and rolling delta wings involving force and pressure measurement and qualitative flow visualization. Complementary PIV investigations have been initiated at Lehigh to determine the origin of critical states encountered during maneuvers.

- *Russell Osborne (WPAFB).* Definition of most important research issues evolving from practical aerodynamic considerations. These issues influence the Lehigh investigations of vortex generators, leading-edge blowing applied to delta wing configurations. In addition, new types of wing configurations under consideration, including the FLAK wing.

- *Alex Shia (WPAFB).* Discussions on practical aspects of buffeting of fins and communication of recent results on consulting project for active control of fin vibration, which influences the direction of the Lehigh work on leading-edge vortex breakdown, as well as on buffeting of fins.

- *Terry Harris (WPAFB).* Discussions of practical issues related to buffeting of fins on F series aircraft and ongoing experiments with group at NASA-Ames, which aids our definition of the most crucial research issues for studies of unsteady leading-edge vortices and buffeting phenomena.

- *George Greene (NASA-Langley).* Discussions on practical issues related to vortex development and interaction with entire aircraft and with fins. These discussions have influenced both our delta wing and buffeting research efforts.

- *Fritze Grosche (DLR (German equivalent of NASA), located in Goettingen).* Discussion of practical aspects of high angle-of-attack aerodynamics including buffeting phenomena.

- *Jurgen Kompenhans (DLR, Goettingen).* Discussion of approaches to quantitative flow visualization of aerodynamic flows at high angle-of-attack.

- *Helmut Eckelmann (Max Planck Institute, Goettingen).* Discussion of issues related to unsteady separated flows. Martin Brede, Ph.D. student from Max Planck Institute, is doing first year of Ph.D. experimental research at Lehigh.

- *John Sheridan (University of Monash, Melbourne, Australia).* Discussion of variety of unsteady separated flow issues. Dr. Sheridan is currently doing a one year sabbatical of experimental research in our laboratories.

- *H. Q. Yang (CFD Research Corporation, Huntsville, Alabama).* Discussions on flow structure above moving delta wings as guidance for SBIR program of CFD Research Corporation.

- *Major Scott Schreck (U. S. Air Force Academy).* Discussions on design of experiments involving pitching delta wings.